

## Preliminary results from the Sprites94 aircraft campaign: 2. Blue jets

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**Abstract.** Initial observations of a newly documented type of optical emission above thunderstorms are reported. "Blue jets," or narrowly collimated beams of blue light that appear to propagate upwards from the tops of thunderstorms, were recorded on B/W and color video cameras for the first time during the Sprites94 aircraft campaign, June-July, 1994. The jets appear to propagate upward at speeds of about 100 km/s and reach terminal altitudes of 40-50 km. Fifty six examples were recorded during a 22 minute interval during a storm over Arkansas. We examine some possible mechanisms, but have no satisfactory theory of this phenomenon.

### Introduction

Over the past century there have been scattered anecdotal accounts of blue or green pillars, columns or rocket like optical phenomena over thunderstorms [Corliss, 1977, 1983; Wilson, 1956; Malan, 1937; Ashmore, 1950; Wright, 1951]. Recently Hammerstrom [1993] reported seeing five events from the cockpit of an American Airlines flight 150 mi. south of Panama. "...I and another pilot...were watching and circumnavigating a large cumulonimbus cloud. About five times, a large discharge of lightning at the top of and within the cloud was followed by a vertical shaft of blue light that propagated from the top of the cloud upward to 100,000 ft. The beam was very straight and the color very distinctly different from the lightning. At the top of this shaft, the column fanned out just before its disappearance."

During the aircraft flights of the Sprites94 Campaign over the central part of the U.S., two thunderstorm related phenomena were documented. In a companion paper, Sentman *et al.* [this issue], discuss "sprites" which are short duration red flashes in the ionospheric D region, sometimes with bluish tendrils extending down to the apparent cloud tops. On flights 1 and 3 July, 1994 UT, we documented many examples of a second distinct phenomenon which is clearly what was reported by Hammerstrom [1993]. We have named them "Blue Jets" based upon their observed characteristics and color [Sentman and Wescott, 1994]. Observations were made from two aircraft instrumented with color and black and white TV cameras. See Sentman *et al.* [this issue] for details of the Sprites94 campaign, the aircraft and optical equipment. The use of two aircraft allowed us to triangulate the positions and altitudes of the blue jets vs. time as they propagated upwards. The triangulations also allowed us to determine the velocities and the angular spreads.

We speculate on possible mechanisms, but none seem very satisfactory.

### Observations

On the evening of July 1, 1994 UT, there was an intense southward moving localized storm extending 350 km east-west across the southern part of Arkansas, with airspace free of clouds to the south and west. Figure 1 shows the National Lightning Detection Network lightning map along with the aircraft track and the locations of some blue jets. The two aircraft made two passes in trailing formation (32.7 km separation) clockwise around Arkansas, keeping the storm to the right side. Fifty six blue jets, but only 4 occurrences of sprites were seen from 02:59:24 to 03:19:43 UT when the first pass ended. Figure 2 shows the rate of occurrence of the blue jets during the first pass. During the second pass from 03:56:00 to 04:15:00 UT there were more diffuse clouds between the aircraft and the flashes. There were 4 events which might have been either jets or sprites, and 11 unmistakable single or groups of sprites, including three spectacular large bright sprites. During another flight on 3 July, 1994 a single blue jet was observed over an active thunderstorm in Kansas at a distance of about 410 km from only the Jet Commander aircraft.

Upward lightning strokes similar to cloud to cloud lightning have been reported in the literature [Everett, 1903; Powell, 1968; Taylor, 1972; Wood, 1951]. During the first pass by the Arkansas storm we recorded nearly two dozen events which we interpret as upward lightning. They were brief and very bright, and extended upward from the cloud tops for much shorter distances than the blue jets. In some cases an upward stroke preceded blue jets by a few frames, and then the jet seems to have originated from the same location. There were some examples of two jets starting out close to each other separated by tens of ms in time. There were three examples of jets starting from the same apparent location and following the same track separated by 50 to 70 ms.

The typical blue jet is observed to appear from the apparent top of the anvil and propagate upwards in a narrow cone, and to flare out as it reaches maximum altitude such that it resembles a trumpet. We measured the cone angle on 18 examples and calculated a mean value of  $14.7^\circ \pm 7.5^\circ$ . The high value was  $31.5^\circ$  and the low value was  $6.5^\circ$ . Figure 3 shows a time sequence of stereo pair TV images 67 ms apart taken from the 90° field of view black and white cameras on the aircraft. This example has been triangulated and yields a terminal altitude of at least 44 km. In most cases the jet seems to fade away all along the cone simultaneously, about 200 ms after it begins. This can be seen clearly 233 ms after the first appearance in the last frames of Figure 3. The jet had a cone angle of  $9.5^\circ$ . All of the jets were quasi-vertical with differing angles. None were magnetic field aligned.

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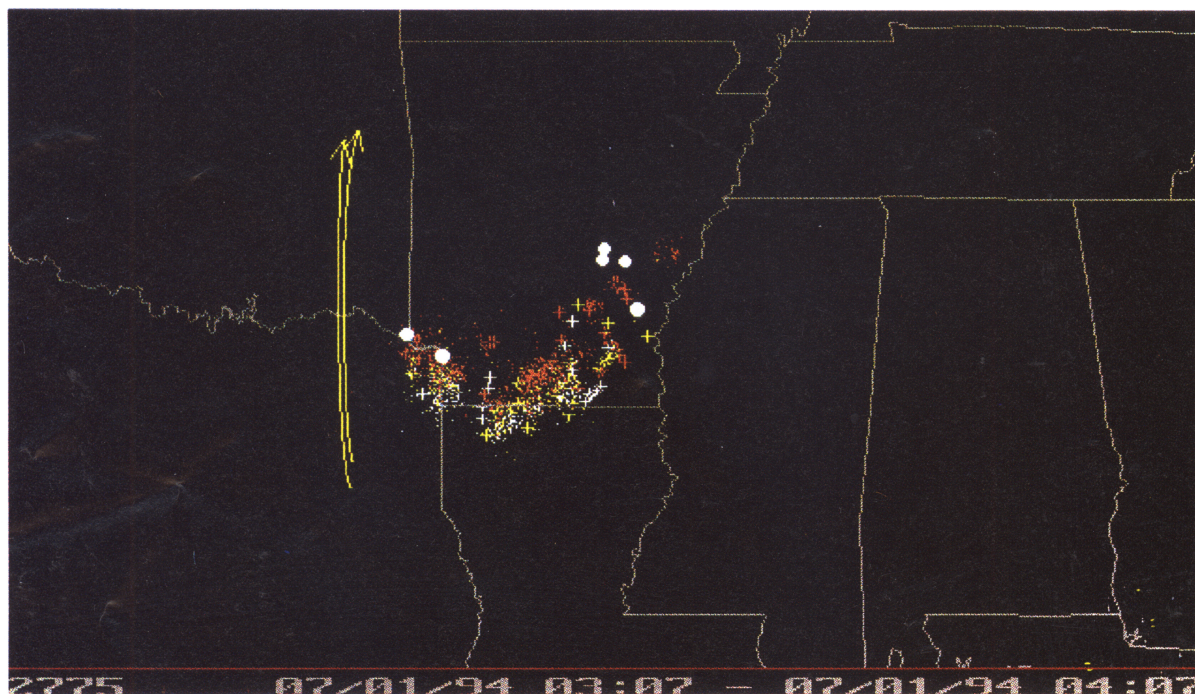


Figure 1. National Lightning Detection Network map, July 1, 1994, showing the cloud to ground strokes during the period of the blue jets (red dots: negative strokes; and red crosses: positive strokes). The locations of six triangulated blue jets are shown as filled white circles. The tracks of the aircraft are shown in yellow.

The altitudes of the two aircraft are accurately known from GPS data recorded on the video frames. We digitize the TV frames using a True Vision Targa M8 board. The digitized frame is then corrected for lens distortion and for pincushion and off axis distortions introduced by the SIT camera. We then use a computer program called "Stereo" written by *H.C. Stenbaek-Nielsen* [personal communication] to fit the stars in the field of view to the positions in the Smithsonian Star Catalogue [1969]. By use of Stereo we can triangulate on any feature visible from both aircraft. The precision of the position determination depends upon several factors: 1) The number of stars in the field of view and star field fit; 2) the distance to the feature from both aircraft; and 3) The brightness and contrast of the feature with respect to the night sky brightness. The palpable front ends of the blue jets lose brightness and contrast with respect to the background as they propagate to altitudes above about 30 km, but we can

reasonably triangulate the position of the front to about 40 km altitude.

Some information is lost in the digitization process. When the jets are observed in real time using the original video tapes the jets can be observed well above 40 km. On some we see what appears to be a hemispherical "shock wave" continuing at the original velocity to perhaps 50 km. We have triangulated the position vs. time of six separate blue jets. The altitude vs. time distribution of these jets are shown in Figure 4 along with the data points for one jet at 03:05:05 UT. The average vertical velocity,  $V_z$  is  $98 \pm 14$  km/s, with a high value of 114.4 and a low value of 78.9 km/s.

The jets differ from sprites in color [Sentman *et al.*, this issue]. We did not obtain a spectrum of a jet, but preliminary analysis of the three color TV signal levels shows that ratio of blue to green in the brightest part of the jet was about 5:1 with no detectable red component. The atmospheric molecules in the altitude range of the blue jets have a similar mixing ratio as at the ground, about 77%  $N_2$  and 11%  $O_2$ . We suggest that the blue jet emissions probably would come primarily from these molecules or their ions. We can also use the auroral emissions as a guide, where the blue emissions are primarily from the first negative bands of  $N_2^+$ . The major bands and their relative strengths are at 391.4 nm (65%), 427.8 nm (20%) and 470.9 nm (4%) [Jones, 1974]. Figure 5 shows the relative response of the color TV system vs. wavelength, and the relative strengths of the first negative bands of  $N_2^+$ . Note that there is almost no response at 391.4 nm.

We have made some estimates of the brightness of blue jets using star calibrations to develop brightness function vs. signal level in the pixel counts. We also use the triangulated positions to calculate the range to the jet and angular size of a pixel. We must make some assumptions about the spectra. Both the color TV and the B/W images can be used with

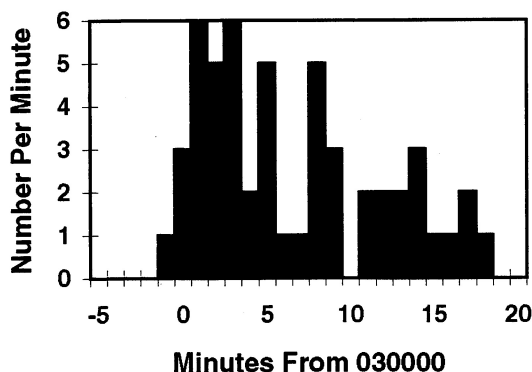


Figure 2. Rate of blue jet occurrence during 22 minute interval of observation during the first pass past the storm shown in Figure 1.

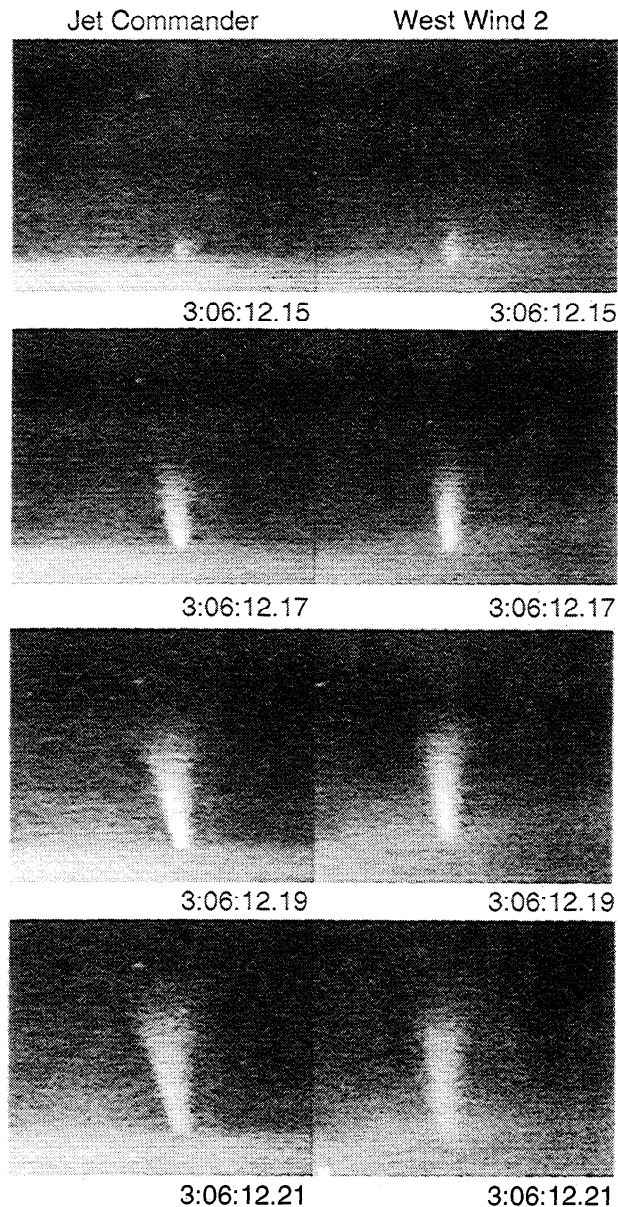


Figure 3. Time sequence of video frames, 67 ms apart, during a blue jet on July 4, 1994, from the Jet Commander, (left) and the Westwind 2, (right). These can be viewed in stereo. Note the brightness is starting to fade all along the jet at 03:06:12.21 in the last pair of frames.

different assumptions. First with the color camera data and assuming that the jet emissions are from the  $N_2^+$  first negative bands the measured brightness would be about 126 kilo Rayleighs (kR) near the center of the jet in the second frame of Figure 3. If the emissions from 391.4 nm band are included the theoretical brightness would be over 500 kR. The black and white camera has a 40% response at 391.4 nm relative to its maximum. If we assume the same emission spectrum and use the B/W camera response, we find that the estimated brightness is 490 kR. The brightness is only about 8 kR near the tip at about 200 ms.

### Discussion

We have presented the first documentation, on black and white and color video recordings of an upper atmospheric

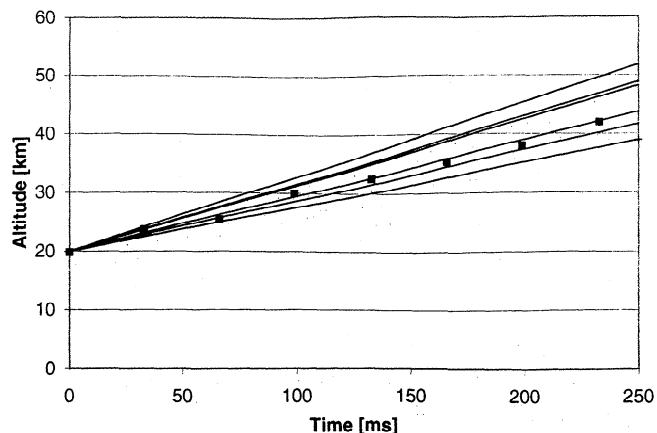


Figure 4. Altitude vs. time plot for blue jet at 03:05:05 UT on July 1, 1994 with the least squares fit to the data, and the least squares lines for five other triangulated jets.

phenomena, which we call "blue jets," associated with thunderstorms. Blue jets may be rarer than the sprites, which are essentially a D region event also associated with mesoscale thunderstorms. It seems possible that the optical phenomena, blue jets, may correspond to VLF radar echoes with similar velocities, terminal altitudes and duration reported by *Rumi*, [1957]. The upward propagation from the anvil top to altitudes near 45 km averages about 100 km/s. The color is mostly blue with some green. The blue jets appear to be much brighter in the black and white images than in the color frames. This may be significant as the color camera has negligible response at the 391.4 nm band of the 1st negative bands  $N_2^+$ , while the black and white camera has 40% response relative to the maximum.

Although the blue jets do not resemble stepped leaders, we note that the propagation velocity is close to that of type-a leaders, which have a uniform earthward speed of about 100 km/s [*Uman*, 1987]. Within the resolution of our video cameras there is little discernible spatial structure in the blue jets and no evidence of the sort of branching and forking

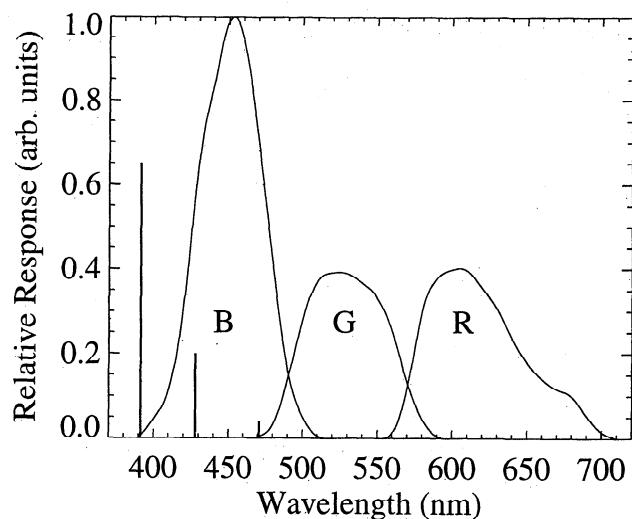


Figure 5. Relative response of the color TV vs. wavelength, and the relative strengths of the first negative bands of  $N_2^+$ . B, G, and R are the responses of the blue, green, and red components.

observed in stepped leaders, but it may be possible that the jets are discharges following some sort of collimated quasi-straight ion trails emanating from the clouds.

On some blue jets we can see what appears to be a faint hemispherical "shock front" ahead of the diffuse leading termination with velocity about the same as the average velocity of the earlier front of the jet. If there is a sonic shock wave it would be at Mach 300, and might produce luminosity, but the excited molecules could not continue to emit for 200 ms. One would expect a traveling shock to produce a brief luminous region traveling upward just behind the shock, and we wonder how a shock wave would be so well collimated.

If nature produces cones of runaway electrons in thunderstorms, then the blue jets might be a result of electron collisions with and ionization of the atmosphere. It is not clear however how the 100 km/s velocity would arise from runaway electrons. A 100 km/s electron has only  $4 \times 10^{-3}$  eV energy, so the electrons would have to have much higher energy and velocity to excite and ionize molecules and atoms. A 100 km/s proton would have about 7 eV energy, but with small mean free path in the atmosphere. Any mechanism producing the blue jets, including particle acceleration, would have to continue for at least 200 ms.

Based upon the preliminary analysis done so far, the following summarizes the salient characteristics of blue jets which a successful theory must explain:

1. Their color is primarily blue.
2. The estimated brightness ranges up to near 500 kR assuming the first negative band emissions of  $N_2^+$ .
3. They are narrowly collimated ( $\sim 15 \pm 7.5^\circ$ ) with an apparent fan out near the top (40 to 50 km).
4. Their apparent vertical propagation speed is  $\sim 100$  km/s.
5. Their apparent source duration is  $\sim 200$  ms at the base of the jet.
6. The overall brightness decays simultaneously along the jet beginning at about 200 to 300 ms.
7. They are often observed to follow upward lightning strokes.
8. There is a faint hemispherical "shock" observed beyond the terminus of some jets traveling at the same speed as the earlier rising portion of the jet.
9. The average occurrence rate was  $\sim 2.8/\text{min}$  in the July 1, 1994 storm during the first 22 minutes of observation.

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